Accurate, Fast Response Meteorological Measurements on the NASA DC-8 for CAMEX-4

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Abstract

1. Instrument Description

This instrument, called the DC-8 Meteorological Measurement System (MMS) measures the in-situ fundamental meteorological quantities that define the environment in which microphysical and dynamical processes are occurring. These quantities are the three-dimensional wind vector (including the vertical wind), the temperature, and the pressure. These quantities are measured at 300 hz, and will be archived at 20hz with the following accuracies and precisions.

- U and V, the horizontal wind components – 1 meter per second accuracy and .1 meter per second precision
- W, the vertical wind component – .1 meter per second precision
- T, temperature – .3K accuracy
- p, pressure – .3mb accuracy

There are four general uses of these measurements envisioned for CAMEX-4. The first of these is to define the upper level structure of the convective storms and hurricanes that are the subject of CAMEX-4, including the locations and magnitudes of updrafts, the mesoscale temperature variations through the eyes and eyewalls of hurricanes, and the horizontal wind variations. This will be done in conjunction with remote measurements, which provide multilevel data but at lower spatial resolution. The second purpose is to perform budget studies of important dynamical quantities, such as heat, momentum and moisture. The simultaneous, high frequency measurement of all the dynamical quantities will allow calculations of vertical fluxes. Third, we can perform turbulence studies with this high-frequency data, including turbulent eddy fluxes and eddy dissipation rates. Finally, the accurate, fast-response temperature measurements are critical in evaluating water and ice saturation mixing ratios that form the basis of any microphysical study.

The method used to make the measurements is based on standard approaches coupled with very careful calibration. To measure temperature, three different sensors (platinum wire thermistors) are used, including one that has a response rate fast enough to deliver signal at frequencies as high as 100 hz. Since the speed of the aircraft results in compressional heating, an accurate and reliable measurement of the Mach number is required to make the correction (which is typically about 25K). The measurement of Mach Number is done with three different measurements of dynamic pressure. The usefulness of the redundant measurements for both temperature and dynamic pressure became apparent during parts of the experiment when ice accumulation blocked some of the sensors (but not all). The standard aircraft dynamic pressure measurement was corrupted by ice on one flight for nearly an hour, while the MMS sensors continued to deliver reliable data.

Winds are measured by the use of differential pressure probes, from which the angle of the flow with respect to the aircraft can be calculated. This angle information, coupled with the true air speed (derived from the dynamic pressure measurement) and the aircraft velocity vector (derived from a gps-updated inertial navigation system with a 3-vector accelerometer) yields the wind components by vector subtraction.

The key to accurate measurements is a systematic approach to all the aspects of the problem. This starts with careful sensor selection and numerical calculations to select the optimum sensor positions on the aircraft. Once selected, pressure and temperature sensors are subject to frequent laboratory calibrations. The inertial navigation unit is also calibrated in the laboratory in order to evaluate, for example, the internal time delays between reported quantities. The final calibration occurs in the field, where the aircraft undergoes pitch, yaw,and roll maneuvers within an air mass that has a high likelihood of being uniform in temperature and wind. The calibration coefficients are evaluated so that measured variations in wind and temperature are minimized. We perform calibrations on each flight because: (1) calibration coefficients typically vary with Mach number, so many maneuvers with different Mach numbers are necessary; and (2) the calibration manuevers on each flight help monitor the state of the instrument by raising a flag if there is a sudden change in calibration coefficients from one flight to the next.

The benefits of the systematic approach can be seen by comparing MMS winds to the standard aircraft winds during one of these maneuvers. This is shown in the first figure at the end of this abstract. The blue and green curves show the roll angle of the aircraft and the sideslip angle respectively as functions of time during a maneuver. Here the aircraft first points from side to side, after which it performs four square turns (essentially a squared loop). The standard aircraft meridional wind (black curve) has a substantial 9 meter per second peak-to-peak variation. The MMS meridional wind, however, has only a 2 meter per second peak-to-peak variation.

2. Accomplishments for CAMEX-4

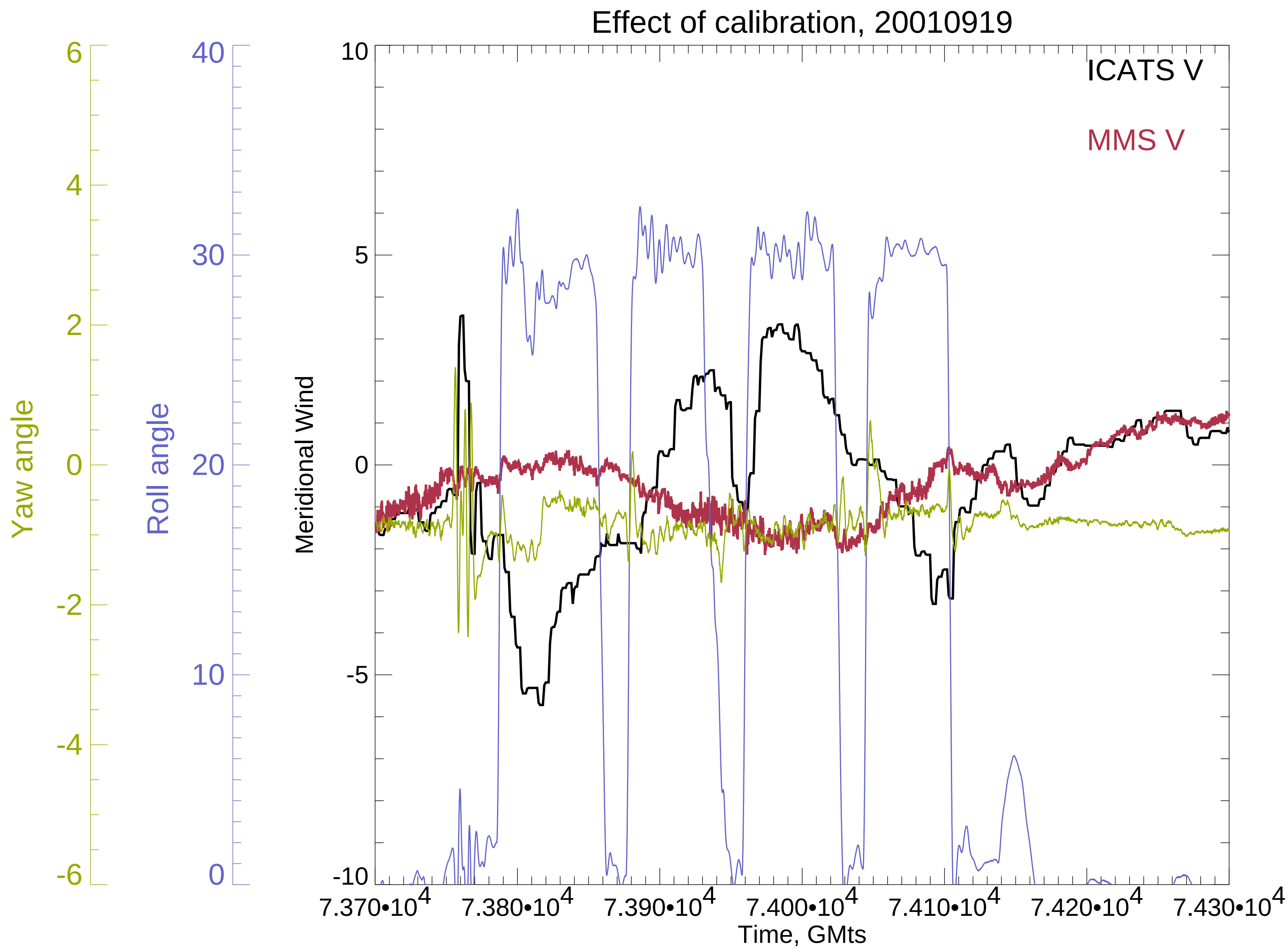
CAMEX-4 is the fourth mission in which the NASA/Ames DC-8 MMS has participated. There have been several improvements in the instrument since the last mission, CAMEX-3. These include the development of a more reliable data system that can handle a higher sampling rate (300 hz vs 10 hz for the previous version). In addition, a superfast temperature sensor was installed, and, in spite of the rigorous conditions (significant turbulence and ice loading), worked on a majority of the flights during CAMEX-4. The second figure after the end of the text shows a preliminary power spectrum from the three temperature sensors. Whereas the traditional platinum resistance sensors (black and blue curves) show significant signal loss at frequencies greater than about 1 hz, the superfast sensor shows behavior consistent with expected meteorological variance to 100hz or more. During the mission, the team produced preliminary data for all the science flights. The data for all but two of these flights was available to the science team on the archive within 6 hours of the end of the flight. Finally, we have developed a data recovery protocol and software to deal with nearly all of the ice accumulation problems encountered during the mission. With the exception of a handful of data dropouts (ranging in length from 10 seconds to 5 minutes), we have continuous, full-length datasets for every science flight. Final data is in preparation at this time (3/29/2002), and should be archived within the next week.

A sample of MMS data from CAMEX-4, and the meteorological context, are shown in the third and fourth figures after the end of the text. The first figure shows an AVHRR 11.5 micron channel image of Tropical Storm Chantal on August 20, on which a portion of the DC-8's flight track at 10.7 km is superimposed. Regions where the vertical wind velocity exceeded 2 meters per second are coded in red. It can be seen that the aircraft passed right next to a region of especially high and cold cloud (with brightness temperatures less than 188K – unusual for the summer season), and that this region, not surprisingly, corresponds to large vertical updrafts and downdrafts. The following figure shows a time series of vertical wind (black), potential temperature (orange), vertical potential temperature flux (blue), and vertical momentum flux (green). The vertical updraft maximum exceeds 20 meters per second, and the time period when the vertical updraft is greater than 2 meters per second is about 40 seconds, or close to 10 km in horizontal extent. There is a broad region of elevated potential temperature (about 150km), consistent with tropical storm structure. Correlations between potential temperature and vertical wind are positive, indicating positive buoyancy for the updrafts and possibly higher vertical velocities at higher elevations. There is a significant upward flux of easterly momentum. If this flux were to be deposited in a 3 km layer above the aircraft, a drag of 10 meters per second in 3 hours would be implied.

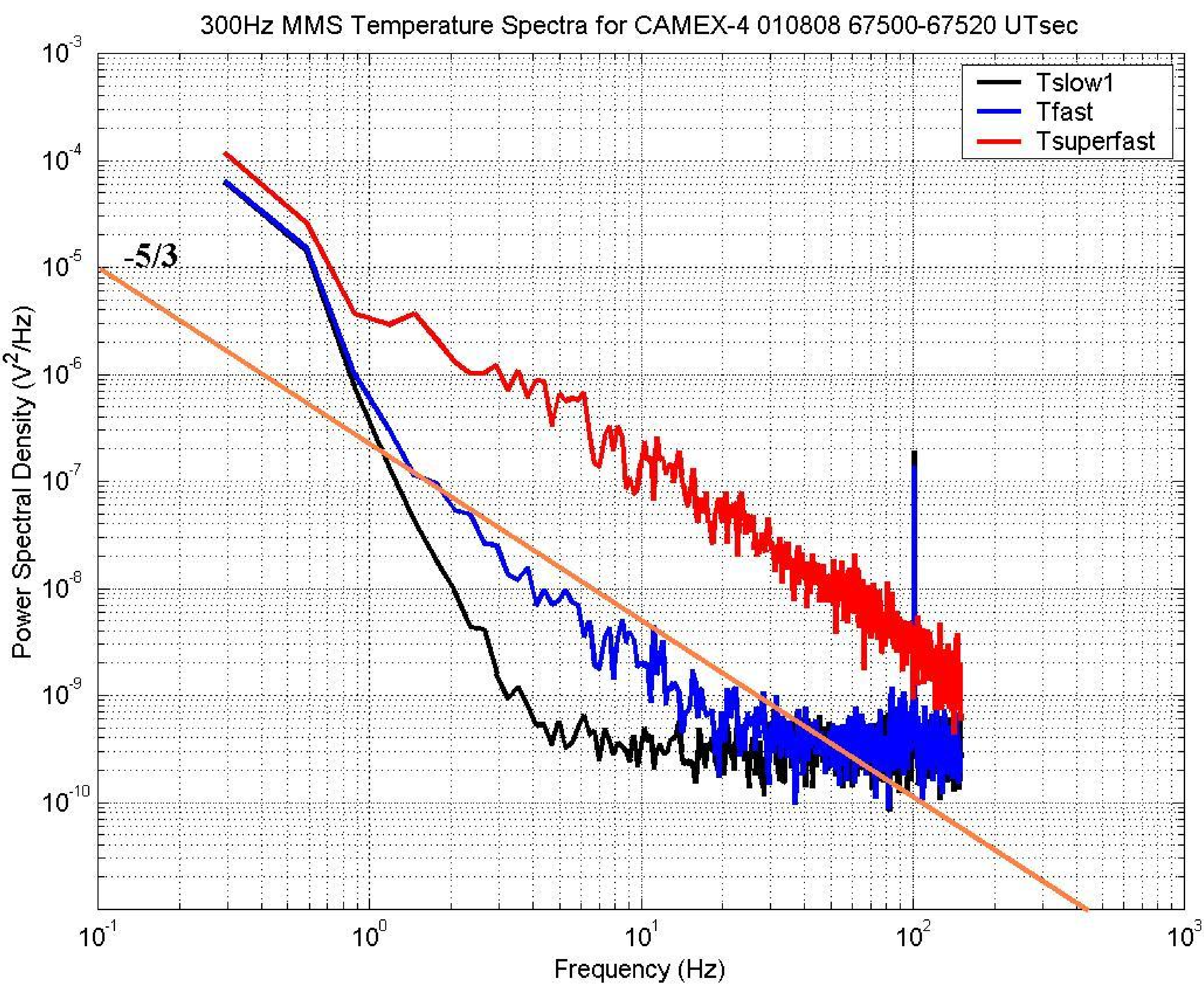
3. Plans

In the next year, we will be analyzing our data to address CAMEX-4 scientific objectives. In particular, we wish to examine carefully the regions of strong vertical motion, evaluating heat, momentum, and moisture fluxes. The simultaneous measurement of temperature, vertical wind, and moisture, along with context information provided by the ER-2 and P-3 based radars (G. Heymsfield of NASA/GSFC and the NOAA Hurricane Laboratory, respectively) will be a powerful tool in understanding the dynamics and history of hurricane and mesoscale convective system updrafts. A second related topic involves the calculation of latent heat release above the aircraft, using upward fluxes of moisture. Third, we expect to use the new superfast temperature sensor to examine turbulence within convective storms. Finally, in collaboration with Dr. R. Herman of NASA/JPL, we will examine the dynamics of ice and water supersaturation in hurricanes and convective systems.

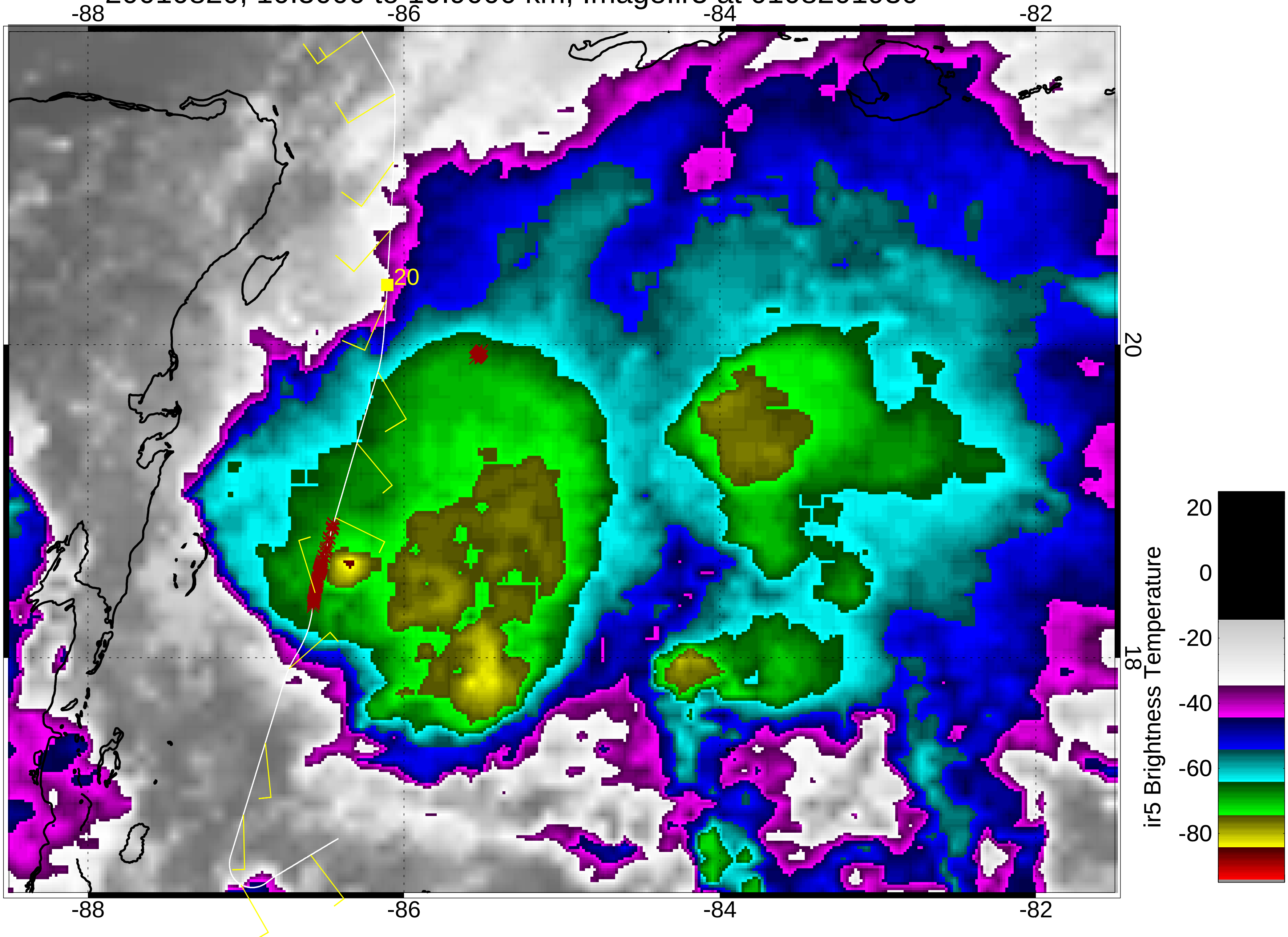
Performing these studies involves collaboration with other investigators, particularly R. Herman of NASA/JPL (in-situ water vapor on the DC-8), A. Heymsfield of NCAR (microphysical measurements), and G. Heymsfield of NASA/GSFC (ER-2 radar). The flights of greatest interest to us include the flight to Tropical Storm Chantal, the three flights to Humberto (as it developed from a Tropical Storm into a hurricane), and the convective flight on September 19, 2001.

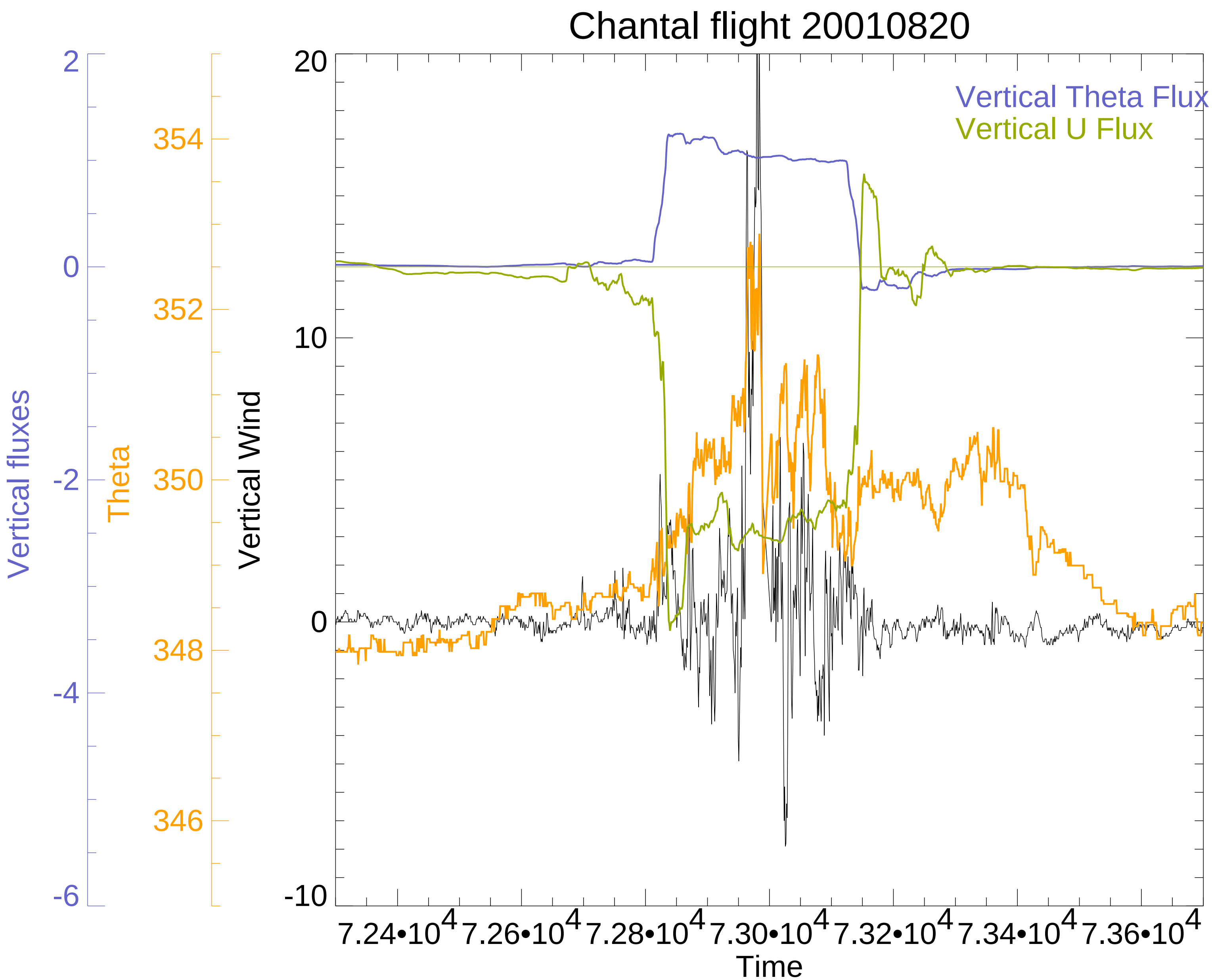


Effect of calibration, 20010919
ICATS V
MMS V
Yaw angle
6
4
2
0
-2
-4
-6
Roll angle
40
30
20
10
0
Meridional Wind
10
5
0
-5
-10
7.370•10^4
7.380•10^4
7.390•10^4
7.400•10^4
7.410•10^4
7.420•10^4
7.430•10^4
Time, GMts


300Hz MMS Temperature Spectra for CAMEX-4 010808 67500-67520 UTsec
Tslow1
Tfast
Tsuperfast
-5/3
Power Spectral Density (V^2/Hz)
Frequency (Hz)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

20010820, 10.5000 to 10.9000 km; Image:ir5 at 0108201930





Chantal flight 20010820
Vertical Theta Flux
Vertical U Flux
Vertical fluxes
2
0
-2
-4
-6
Theta
354
352
350
348
346
Vertical Wind
20
10
0
-10
7.24•10^4
7.26•10^4
7.28•10^4
7.30•10^4
7.32•10^4
7.34•10^4
7.36•10^4
Time